Analytical Treatment of the Relationships between Soil Heat Flux/Net Radiation Ratio and Vegetation Indices

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Relationships between leaf area index (LAI) and midday soil heat flux/net radiation ratio (G/R_n) and two more commonly used vegetation indices (VIs) were used to analytically derive formulas describing the relationship between G/R_n and VI. Use of VI for estimating G/R_n may be useful in operational remote sensing models that evaluate the spatial variation in the surface energy balance over large areas. While previous experimental data have shown that linear equations can adequately describe the relationship between G/R_n and VI, this analytical treatment indicated that nonlinear relationships are more appropriate. Data over bare soil and soybeans under a range of canopy cover conditions from a humid climate and data collected over bare soil, alfalfa, and cotton fields in an arid climate were used to evaluate model formulations derived for LAI and G/R_n, LAI and VI, and VI and G/R_n. In general, equations describing LAI–G/R_n and LAI–VI relationships agreed with the data and supported the analytical result of a nonlinear relationship between VI and G/R_n. With the simple ratio (NIR/Red) as the VI, the nonlinear relationship with G/R_n was confirmed qualitatively. But with the normalized difference vegetation index (NDVI), a nonlinear relationship did not appear to fit the data.

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INTRODUCTION

One of the main objectives of some recent hydrometeorological studies has been to test the feasibility of evaluating the surface energy and water balance at regional scales with models using remote sensing information (Andre et al., 1986; Sellers et al., 1988; van de Griend et al., 1989; Kustas et al., 1991). The rationale for using remotely sensed data is that the information may provide estimates of important parameters for energy balance modeling over large areas. The surface energy balance equation is usually composed of four terms assuming that advection and storage of heat in the vegetated layer is negligible (Brutsaert, 1982):

$$R_n + G + H + \mathrm{LE} = 0, \tag{1}$$

where R_n is net radiation, G the soil heat flux, H the sensible heat flux, and LE the latent heat flux all in units of W m^{-2}. In (1), the major emphasis is in determining LE because of its impact on climate and the hydrologic cycle.

When integrating the surface energy balance over a 24-h period, G is commonly assumed to be negligible (e.g., Price, 1982; Seguin and Itier, 1983). However, observations over arid and semiarid regions with sparse canopy cover have found daily G/R_n values on the order of 0.1–0.2 (Kustas et al., 1990; Brunel, 1989). Hence, even on a daily basis, G may not be negligible for certain surfaces. Moreover, when extrapolating midday estimates of the energy balance components from remotely sensed data to daily values (e.g., Jackson et al., 1977; Kustas et al., 1990) or modeling (1) at shorter time steps over the diurnal cycle (e.g., Taconet et al., 1986; Gurney and Camillo, 1984), G cannot be neglected over many land surfaces. Furthermore, recent experimental evidence suggests that for a range of surface conditions, the evaporative fraction $\mathrm{LE}/(R_n + G)$ is relatively constant over the daytime period (Shuttleworth et al., 1989). This result, if widely applicable, could greatly simplify the estimation of regional scale LE if the evaporative fraction and the quantity $(R_n + G)$ could be determined primarily with satellite remote sensing.

In evaluating the relative importance of G and for simple modeling parameterizations, the ratio of G/R_n has been computed over different surfaces. For full canopy covered conditions (excluding forested areas), values of the G/R_n ratio generally lie between 0.05 and 0.10 (Monteith, 1973; Choudhury et al., 1987). For bare soil, values on the order of 0.3–0.4 have been documented (Brutsaert, 1982), although a review of experimental results by Choudhury et al. (1987) suggested that a range from 0.2 to 0.5 has been observed. Thus, for many naturally vegetated surfaces, and for a significant part of the growth cycle of many agricultural crops, a significant fraction of the soil surface is exposed to radiation, which results in the G/R_n ratio taking on a range of values anywhere from 0.05 to 0.5 during the day.

Field studies (e.g., Fuchs and Hadas, 1972) have documented that the G/R_n ratio is not constant for a given surface over the day. A simple analytical expression for adjusting the value of G/R_n to account for this effect has been proposed (Camuffo and Bernardi, 1982) and, in theory, could be applied once the coefficients are fit to the observations. Fortunately, observations suggest that G/R_n is relatively constant for several hours surrounding midday (e.g., Clothier et al., 1986). Hence techniques for computing the surface energy balance can treat G/R_n as a constant for a particular surface over a significant part of the daytime period.

Jackson (1985) noted that most techniques for measuring or modeling G provide local estimates and therefore would not be appropriate for regional energy balance studies. Nevertheless, experimental results by Clothier et al. (1986) and Kustas and Daughtry (1990) suggest that G/R_n can be reasonably estimated using a remotely sensed vegetation index. These results are consistent with observations suggesting that remotely sensed vegetation indices can be used as a surrogate for plant phytomass, leaf area index, and percent cover (Hinzman et al., 1986; Ormsby et al., 1987). These would be the primary factors affecting the magnitude of the G/R_n ratio (Kustas and Daughtry, 1990). Thus difficulties in obtaining representative values of G for large scale energy balance work may be somewhat alleviated by using vegetation index maps derived from satellite data (Tucker et al., 1985; Goward et al., 1985).

The functional form of the relationship between vegetation indices (VI) using the ratio of near-infrared (NIR) over red (Red) reflectances (NIR / Red) and G/R_n was found to be linear by Clothier et al. (1986) and Kustas and Daughtry (1990). However, an equation employed by Jackson et al. (1987) used an expression from K. L. Clawson (unpublished) that calculates G/R_n as an exponential function of the normalized difference vegetation index (NDVI = (NIR − Red) / (NIR + Red)). In this study, formulas were derived analytically from equations describing LAI–G/R_n and LAI–VI relationships in order to reveal the functional form of the relationship between G/R_n and VI. This work relied on observations from Choudhury et al. (1987), who showed that G/R_n can be expressed as an exponential function of LAI, and on the results of Asrar et al. (1984) and Huete (1988), who found VIs could also be expressed as an exponential function of LAI.

Observations of G/R_n and VI in a humid climate for a soybean crop over a range of canopy cover and LAI and data from agricultural crops in an arid region (Kustas and Daughtry, 1990) were used to compare with the model equations and with past studies. This analysis considered values of G/R_n around midday under clear sky conditions with the spectral data collected under relatively small solar zenith angles (i.e., less than 45°) to minimize the solar position effects on the measured reflectance (Huete, 1987; Ranson et al., 1985).

This study investigated only two more commonly used vegetation indices, namely, NIR / Red ratio and NDVI. These VIs are sensitive to soil background reflectance properties (e.g., Huete et al., 1985; Baret and Guyot, 1991). While other VIs have been developed to reduce this soil background effect (e.g., Huete, 1988; Clevers, 1989; Baret et al., 1989), most need the soil line equation, which may be difficult to define using satellite observations.

APPROACH

In deriving a set of equations describing the relationship between G/R_n and VI, the main assumption was that magnitude of midday G/R_n is essentially a function of the amount of vegetated cover. Vegetated cover is related to the amount of vegetative biomass and LAI. Furthermore, studies have documented that the extinction of Rn inside a plant canopy can be expressed as an exponential decay function (Monteith, 1973; Ritchie, 1972; Ross, 1981). Although this is an empirical approximation and models exist which treat separately the balance of long and shortwave radiation inside canopies (e.g., Van de Griend and van Boxel, 1989), the exponential decay for R_n has lead to a simple conceptual model of G/R_n versus LAI (Choudhury et al., 1987):

$$G/R_n = C\exp(-\beta\,\mathrm{LAI}), \tag{2}$$

where C is G/R_n for bare soil (≈ 0.3–0.4) and β is the extinction coefficient, which is of order 0.5 but varies somewhat with vegetation type and solar zenith angle (Monteith, 1973; Ross, 1981). Although Choudhury et al. (1987) interpreted Eq. (2) as an empirical expression, we regarded it as a physically based relationship because it describes the main factors affecting the magnitude of G, namely, the amount of vegetated cover (LAI) and amount of R_n reaching the soil surface.

In the near-infrared-red (NIR–Red) wavelength space Huete (1988) showed that the slope of the vegetation isolines, S_{VI}, is given by

$$S_{VI} = S_S \exp[2\,(\tau_{Red} - \tau_{NIR})\,\mathrm{LAI}], \tag{3}$$

where S_S is the slope of the soil line and τ_{Red} and τ_{NIR} are the canopy extinction coefficients in the Red and NIR wavebands, respectively. The intercept described in Huete (1988) was assumed negligible, which resulted in S_{VI} equaling the NIR / Red ratio vegetation index. Thus Eq. (3) can be rewritten in more general terms as

$$\mathrm{NIR} / \mathrm{Red} = A \exp(\tau\,\mathrm{LAI}), \tag{4}$$

where A ($\equiv S_S$) and τ [$\equiv 2\,(\tau_{Red} - \tau_{NIR})$] are determined experimentally. When LAI was substituted as a function of VI from Eq. (4) into Eq. (2), the expression between G / R_n and NIR / Red was reduced to

$$G / R_n = C A^{\beta/\tau} (\mathrm{NIR} / \mathrm{Red})^{-\beta/\tau}. \tag{5}$$

From Eq. (5) it is seen that a linear relationship would exist if $-\beta \approx \tau$; otherwise, Eq. (5) suggests that a nonlinear relationship is more appropriate.

The assumption of no intercept for the vegetation isolines in order to derive this simple expression does not agree with field data (e.g., Huete, 1988) nor with reflectance simulations by Baret and Guyot (1991) using the SAIL model (Verhoef, 1984). By omitting the intercept the effects of the background soil reflectance, which complicates the application of spectral vegetation indices for inferring canopy properties, were not considered. When an intercept was included in Eq. (4), a more complicated expression similar in form to Eq. (7) was obtained. Hence the conclusion made with Eq. (5) was not affected by this simplification (see below).

Past studies document that a modified Beer's law expression can describe the relationship between NDVI and LAI (Asrar et al., 1984; Hatfield et al., 1985; Asrar et al., 1989), that is,

$$\mathrm{NDVI} = A\,[1 - B \exp(-\tau\,\mathrm{LAI})], \tag{6}$$

where the quantity $A(1 - B)$ represents the value of NDVI for bare soil (LAI = 0), A the value of NDVI when LAI is maximum (i.e., LAI of order 4 or greater), and τ is the extinction coefficient. Substitution of Eq. (6) as a function of LAI into Eq. (2) produced an expression between G / R_n and NDVI having the following form:

$$G / R_n = C\,[-\mathrm{NDVI} / (A\,B) + 1 / B]^{\beta/\tau}. \tag{7}$$

From Eq. (7) it can be deduced that a linear relationship would exist if $\beta \approx \tau$.

Perry and Lautenschlager (1984) showed that NIR / Red and NDVI vegetation indices are not independent and are related by the following expression:

$$\mathrm{NDVI} = (\mathrm{NIR} / \mathrm{Red} - 1) / (\mathrm{NIR} / \mathrm{Red} + 1). \tag{8}$$

When Eq. (4) replaced NIR / Red in Eq. (8), the resulting NDVI–LAI relationship differed markedly from Eq. (6). When this expression was substituted into Eq. (2), a solution between G / R_n and NDVI could not be obtained. Baret and Guyot (1991) compared SAIL model simulations of VI with Eq. (6) and concluded that Eq. (6) was a reasonable description of the relationship between VI and LAI. They also demonstrated that soil background reflectance introduced significant scatter in the NDVI–LAI relationship.

Equations (5) and (7) were derived using simplified and / or empirical relationships between LAI and G / R_n, and LAI and VI. This creates some uncertainty as to the conclusions one may draw from this analysis and from evaluating these relationships with field data. Still, it does provide some insight as to the conditions which can lead to a linear relationship between VI and G / R_n. Clearly, one would not expect $\beta \approx \tau$ since these absorption-scattering coefficients represent different waveband regions. Therefore, it was concluded that an acceptable analytically based formula for the relationship between G / R_n and VI shown in Eqs. (5) and (7) would be a nonlinear expression of the form

$$G / R_n = a\mathrm{VI}^b. \tag{9}$$

DATA DESCRIPTION

BARC 89 Field Description

Data were collected in two experiments to provide a wide range in environmental conditions. One field experiment (MAC 88) was conducted in an arid climate in June 1988 as part of an interdisciplinary study at the Maricopa Agricultural Center in Central Arizona (33.08°N, 111.98°W). Continuous measurements of soil heat flux, soil temperature, and net radiation were recorded over four agricultural fields containing bare soil, cotton, and alfalfa. Further details can be found in Kustas and Daughtry (1990). The second study was conducted over bare soil and soybeans in a humid environment (BARC 89) and is described below [see also Daughtry et al. (1992) and Van Oevelen (1991) for more details]. Data were collected at the South Farm of the Beltsville Agricultural Research Center (BARC; 39.03°N, 76.92°W) near Beltsville, Maryland. The experiment was conducted from June to October 1989.

The weather conditions during the experimental period can be characterized as gentle southwest and south winds bringing fairly humid maritime tropical air masses into the region. The average air temperature in the summer is about 25°C with an average relative humidity of 68%. The daily maximum temperature in

July and August are commonly near or above 30°C. The average fractional cloud cover in the summer is approximately 0.60.

The soil at the experimental site is a silt loam (Codorus silt loam with a 1–2% slope). There was a total of 12 plots, four bare soil plots, and eight plots with soybeans, an adapted cultivar (*Glycine max* Merr. "Williams 82"). The soybeans were planted with a row spacing of 0.18 m (narrow row spacing) or 0.76 m (wide row spacing), each on four 15 m × 35 m plots. The direction of the rows was north–south. The day of planting was also different; for two of the 0.18-m-row plots soybeans were planted on 31 May, Day of Year (DOY) 160; the other two on 13 June, DOY 173. The same was done for the 0.76-m-row plots. All plots were irrigated with 75 mm of water on 1 September 1989 (DOY 244). Preemergence herbicides were applied for weed control.

Net Radiation and Soil Heat Flux Data

Measurements to determine net radiation and soil heat flux were acquired continuously at 10-s intervals and stored as 15-min means from DOY 188 to 297. The phytomass, multispectral and soil moisture data were collected on selected days. Table 1 summarizes the instruments situated in some of the plots during the experiment along with a listing of the model and manufacturers.[1] The data were recorded with Campbell Scientific Inc. (CSI) dataloggers (CSI Model 21x micrologger) and multiplexers (CSI Model AM32).

Multispectral Data

Multispectral data were acquired with a Barnes modular multiband radiometer (Model 12-1000) with a 15° field of view. Its wavelength bands are given in Table 2. The radiometer and a 35 mm camera were attached to a boom mounted on a pickup truck. The instruments were elevated about 7.6 m above the soil surface and positioned with a nadir view angle. This mobile, ground-based remote sensing system allowed for relatively rapid acquisition of multispectral data over all plots. The procedures and conditions described by Biehl and Robinson (1983) were used for obtaining reflectance factor data. A 1.2-m panel painted with $BaSO_4$ was used as a reference surface.

[1] Trade and company names are given for the benefit of the reader and do not imply any endorsement by the USDA-ARS.

Table 2. Description of the Barnes[a] 12-1000 Radiometer

Band	*Wavelengths (μm)*
1	0.45–0.52
2	0.52–0.60
3	0.63–0.69
4	0.76–0.90
5	1.15–1.35
6	1.55–1.75
7	2.08–2.35

[a] Barnes Engineering, Stamford, CT.

Agronomic Data

Green leaf area index, stage of development, fresh and dry phytomass, and percent soil cover were measured approximately weekly. In each plot five randomly selected 0.5-m lengths of row were harvested on each date, separated into green leaves, brown leaves, stems (including petioles), and pods, dried at 70°C to constant weight, and weighed. Green leaf area was calculated using the relationship between leaf area and leaf dry mass of a subsample of leaves and the dry mass of all green leaves. Leaf area index was computed as the ratio of green leaf area divided by the soil area sampled.

Soils Data

In order to calculate the surface soil heat flux, the heat capacity of the soil from 0–5 cm and the soil conductivity to correct heat flow plate values were needed. This required knowledge of the soil texture and soil moisture for the upper 5 cm. For the textural analysis, 15 soil

Table 1. Manufacturer, Model Numbers, and Quantity of Instrumentation Used in the BARC 89 Experiment for Determining Net Radiation and Soil Heat Flux

Plant Date (DOY)	*Row Spacing (cm)*	*Soil Temperature[a] (− 2.5 −7.5 cm)*		*Soil Heat Flux[b]*	*Net Radiation[c]*
Bare soil plot	–	2	–	2	1
160	18	2	1	2	1 over rows
160	76	4	4	4	1 over rows, 1 between rows
173	18	2	1	2	1 over rows
173	76	4	4	4	1 over rows, 1 between rows

[a] CSI 107B Temperature Probe (Campbell Scientific Inc., Logan, UT).
[b] REBS HFT-3 Soil Heat Flux Transducers (Radiation and Energy Balance Systems, Inc.).
[c] REBS Q*4 Net Radiometers (Radiation and Energy Balance Systems, Inc.).

samples were collected along transects in the study area. The mean percentages of sand, silt and clay were 38, 49, and 13, respectively, using the hydrometer method of Day (1965). Soil moisture was determined gravimetricly from samples of the 0–5 cm layer collected twice a week from all 12 plots. Normally four samples were collected in the plots where there were measurements of R_n and G while two samples were obtained from the other plots. Mean bulk density for the 0–5 cm layer of soil was estimated several times during the experiment.

Since daily values of soil moisture were not available, soil moisture was interpolated between measurements. Figure 1 is a time plot showing values of measured and interpolated daily soil moisture averaged for the plots that contained measurements of R_n and G, and rainfall totals of events that occurred during the experimental period. Interpolation between soil moisture measurements required precipitation between measurements to be taken into account. This meant that, on days with rainfall, the soil moisture content was set at a maximum, or a fraction thereof, depending on the amount of rainfall and the measured or interpolated soil moisture value. The procedure is described more fully in Van Oevelen (1991).

DATA ANALYSIS

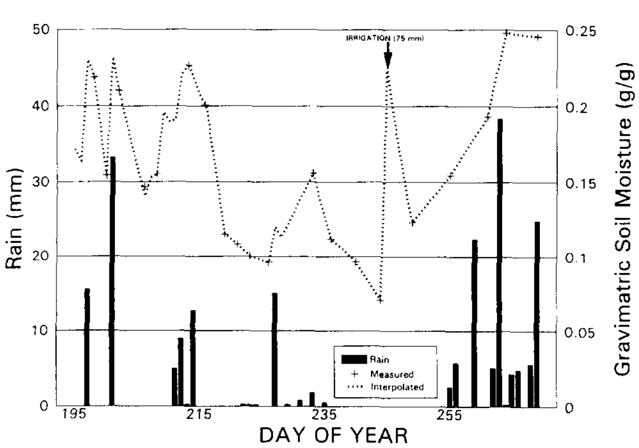
Determination of the Soil Heat Flux G at the Surface

In order to calculate the surface soil heat flux, the change in heat storage above each plate was added to the plate value,

$$G = G_{0.05} + S, \tag{10}$$

where $G_{0.05}$ is the flux density (W m^{-2}) measured by the plates at 5 cm and S is the storage term. The storage term was estimated by the following formula:

Figure 1. Measured and interpolated gravimetric soil moisture content and measured precipitation during the course of the BARC 89 experiment.



$$S = 55.56(1.94\theta_m + 2.50\theta_c + 4.19\theta)(T_{s(i)} - T_{s(i-1)}). \tag{11}$$

The symbols θ_m, θ_c, and θ represent volume fractions of minerals, organics, and water in the 0–5 cm layer, respectively and the associated coefficients are from De Vries (1963). The rate of change in soil temperature, T_s, over time for the layer was estimated using measurements at 2.5 cm and a 15-min time step represented by the subscript i.

For the 0.76-m row spacing, a weighted average of the surface soil heat flux was determined by means of the fractional cover (f_v) given by the photographs. This involved multiplying the average of the two measurements of soil heat flux made adjacent to the row crops by f_v while multiplying the average of the other two in the opening between the rows by $(1 - f_v)$. Because the soybeans in the 0.18-m rows quickly covered the soil, an equally weighted mean was used. Similarly, for the bare soil, an equally weighted average was used. Further details of the method for calculating surface soil heat flux can be found in Kustas and Daughtry (1990).

Differences between the diffusivity of the soil, heat flow transducers, and medium used to calibrate the plate may be significant enough to require a correction to the plate values (Phillip, 1961; Fritschen and Gay, 1979). This basically involves adjusting the calibration of the plates. These corrections were obtained with a procedure outlined in De Vries (1963) for calculating soil diffusivities and an expression from Philip (1961) for adjusting the calibration factor of the flux plate. About a 5% correction, on average, was made to plate calibration factors.

Correction to Net Radiation Measurements

The double dome net radiometers (Q*4) used in this study tend to overestimate the net radiation. More specifically, they overestimate daytime (positive) values and underestimate nighttime (negative) values. The correction formula used for the daytime values was the following (Nie et al., 1992):

$$R_n = 0.8971 R_{nm} + 1.85, \tag{12}$$

where R_{nm} and R_n are the measured and corrected net radiation values, respectively.

On average the correction with Eq. (12) is about 10% of the measured daytime values. As pointed out by Field et al. (1992) and Oliver and Wright (1990), the net longwave and shortwave contributions to R_n are needed to adjust Q*4 measurements for a range of environmental conditions, although it may be possible to use net shortwave estimates once the calibration constant for the net longwave is known (Oliver and Wright, 1990).

However, for this analysis, the correction given above was considered adequate since the functional relationship between G/R_n and VI should not change

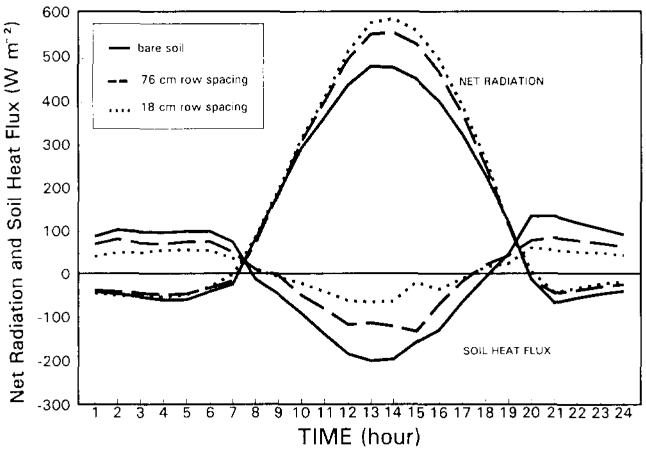


Figure 2. Values of net radiation and soil heat flux from DOY 210 for three different vegetation cover conditions. Values of LAI were around 0, 1, and 4.5 for the bare soil, 76 cm and 18 cm row spacing, respectively. Solar noon occurred approximately 1330 EDST.

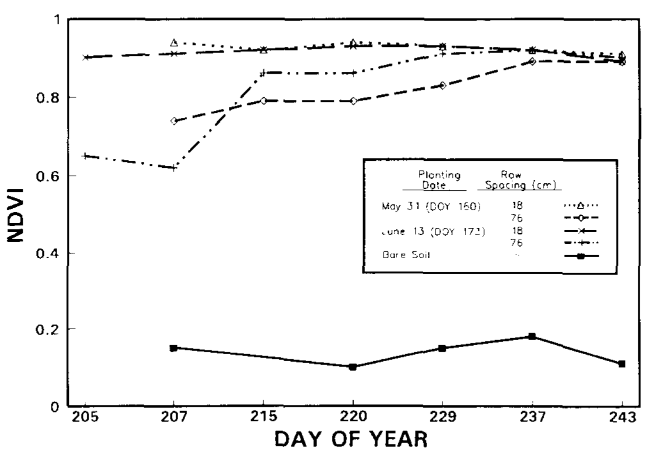
due to a less accurate adjustment to $Q*4$ values (Kustas and Daughtry, 1990). Unless otherwise specified, the corrected soil heat flux and net radiation values were used in the subsequent analysis.

Results

In Figure 2, data for a clear day are illustrated and show the range in values of net radiation and soil heat flux as affected by the amount of vegetation and meteorological conditions. In general, note that the variation in the magnitude of soil heat flux as a function of the amount of vegetation is opposite to the differences in net radiation. In other words, G decreases going from bare soil to full vegetated cover while R_n increases.

In Figures 3 and 4, the values of NDVI and LAI are plotted against the Day of Year (DOY). From these figures it can be seen that once a LAI of order 4 is reached, NDVI becomes constant at about 0.9. Also note that most of the measurements for the vegetated plots were collected at high leaf area indices, resulting in relatively small differences in NDVI values among the plots.

Figure 3. NDVI versus DOY for the different plots.



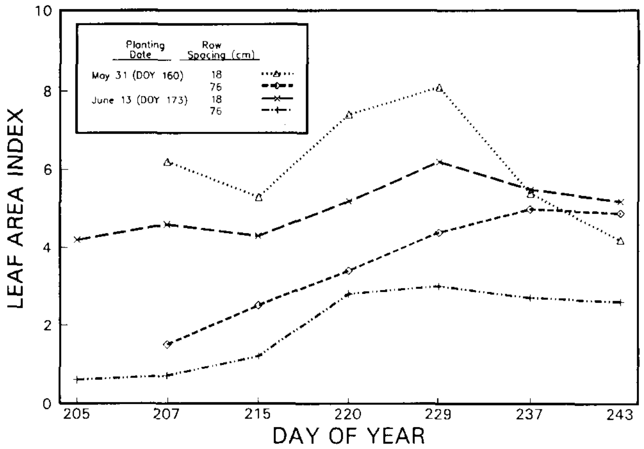


Figure 4. LAI versus DOY for the different plots.

Data for the analyses were taken from days with spectral measurements. These particular days were clear to mostly sunny, allowing for easier interpretation of the spectral data. About 30% of the days were suitable for spectral observations near midday (i.e., minimal cloudiness). Midday values of G/R_n (~1330 Eastern Daylight Savings Time, EDST) were computed by averaging the measurements from the two 15-min values of G and R_n surrounding 1330 EDST.

ANALYSIS AND DISCUSSION

Relationships between G/R_n and VI versus LAI

The data listed in Table 3 were used to estimate the coefficients in Eqs. (2), (4), and (6). Values of the coefficients in Eq. (2), derived with the data from the present study, are given in Table 4 along with magnitudes of the constants from previous work.

The extinction coefficient β calculated using all the data from Table 3 is about half that found by Choudhury et al. (1987) and others. When data with the same range in LAI were taken (i.e., LAI < 4), the calculated extinction coefficient is similar to ones previously reported. These results suggest that beyond a certain value of LAI, the relationship between G/R_n and LAI is essentially constant. The two relationships are shown on logarithmic scale in Figure 5 [see also Fig. 3 from Choudhury et al. (1987)]. The scatter in G/R_n values for LAI > 4 is not surprising since, for full canopy cover, values for G/R_n from 0.05 to 0.1 have been reported (Monteith, 1973).

Estimates of the NIR/Red ratio and NDVI were

Table 3. Data Used in Evaluating the Relationships between LAI and Midday G/R_n, LAI and VI, and VI and Midday G/R_n

Surface	Row Spacing (cm)	DOY	NDVI	NIR / Red	LAI	$-G/R_n$
			BARC 89			
Bare soil	N / A	207	0.15	1.3	0	0.40
		220	0.10	1.2	0	0.32
		229	0.15	1.4	0	0.29
		237	0.18	1.4	0	0.41
		243	0.11	1.3	0	0.40
Soybean	18	207	0.94	29.7	6.2	0.13
		215	0.92	25.2	5.3	0.12
		220	0.94	30.5	7.4	0.03
		229	0.93	25.8	8.1	0.08
		237	0.92	25.1	5.4	0.07
		243	0.91	21.8	4.2	0.09
Soybean	18	205	0.90	18.7	4.2	0.16
		207	0.91	21.2	4.6	0.11
		215	0.92	22.9	4.3	0.11
		220	0.93	27.5	5.2	0.03
		229	0.93	26.5	6.2	0.06
		237	0.92	25.3	5.5	0.05
		243	0.89	16.8	5.2	0.06
Soybean	76	205	0.65	4.6	0.6	0.34
		207	0.62	4.3	0.7	0.27
		215	0.86	12.8	1.2	0.15
		220	0.86	13.7	2.8	0.11
		229	0.91	20.4	3.0	0.10
		237	0.92	23.5	2.7	0.10
		243	0.90	18.3	2.6	0.10
Soybean	76	207	0.74	6.8	1.5	0.15
		215	0.79	10.3	2.5	0.18
		220	0.79	8.4	3.4	0.04
		229	0.83	10.9	4.4	0.10
		237	0.89	16.4	5.0	0.06
		243	0.89	16.8	4.9	0.13
			MAC 88			
Bare soil	N / A	162	0.09	1.2	0	0.32
		165	0.09	1.2	0	0.29
Alfalfa	N / A	162	0.64	5.5	1.6	0.21
		163	0.79	8.7	1.6	0.20
		165	0.80	9.5	1.6	0.16
Cotton	100	163	0.30	1.9	0.2	0.28
		163	0.39	2.3	0.4	0.31
		163	0.52	3.2	0.5	0.21
		165	0.30	1.8	0.2	0.26
		165	0.41	2.4	0.4	0.30
		165	0.60	4.1	0.8	0.23

compared to corresponding LAI values. Exponential relationships given by Eq. (4) for NIR / Red ratio and Eq. (6) for NDVI are illustrated in Figure 6. Equation (6) fits the data rather well (Fig. 6a) while the NIR / Red and LAI values (Fig. 6b) appear to follow a linear instead of exponential [cf. Eq. (4)] relationship. Linear

Table 4. Values of the Coefficients for $G/R_n = C\exp(-\beta\ \mathrm{LAI})$, Eq. (2), from the Present Study and from Previous Work

C	β	Source	Coefficient of Determination R^2
0.4	0.5	Choudhury et al. (1987)	0.87
0.34	–	Fuchs and Hadas (1972)	
0.22–0.51	–	Idso et al. (1975)	
–	0.45–0.65	Monteith (1973)	
–	0.4	Ritchie (1972)	
0.29	0.26	Present study	0.72
0.34	0.46 (LAI < 4)	Present study	0.84

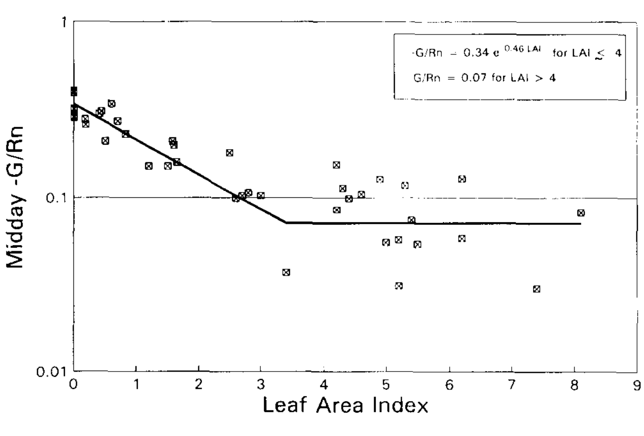
relationships between the NIR / Red ratio and LAI have been observed for soybean (Holben et al., 1980) and other agricultural crops (e.g., Hatfield et al., 1985; Wiegand et al., 1990). Table 5 lists the least squares regression results, which support the above conclusions. From this analysis, it appears that the simplifications which lead to Eq. (4) are not supported by the data.

In an earlier version of this article, Dr. R. D. Jackson showed that substitution of a linear equation between NIR / Red and LAI into Eq. (8) produced a curvilinear function which behaved similarly to Eq. (6), but did not fit the data as well. If a linear relationship between NIR / Red and LAI was adopted, then exponential relationships would be obtained between G/R_n and NIR / Red and NDVI via Eqs. (2) and (8). However, inside the exponential for both relationships are expressions which prohibit the VIs from being treated as independent variables [cf. Eqs. (5), (7), and (9)]. Hence there is no direct way of evaluating these equations using G/R_n and VI data without first fitting the linear equation between NIR / Red and LAI.

Analytical versus Experimental Relationships

Linear regression results between midday G/R_n and VIs using the data in Table 3 are shown in Table 6

Figure 5. Midday G/R_n versus LAI for the data in Table 3. Note a logarithmic scale is used for the ordinate.



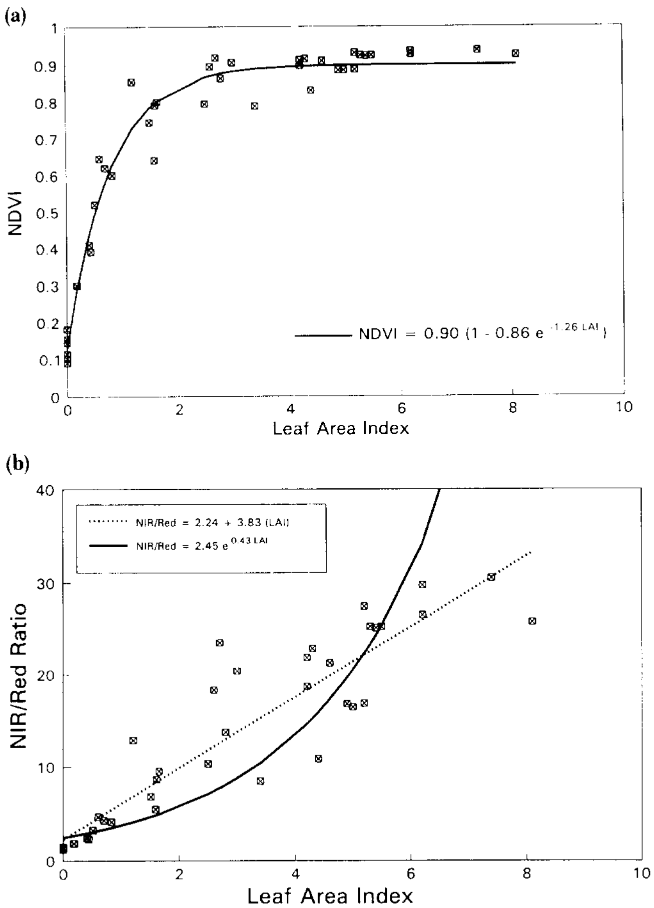


Figure 6. Vegetation index versus LAI using a) NDVI with the curve fit given by Eq. (6) and b) using NIR / Red with the curve fit given by Eq. (4) and using a linear equation.

along with results from previous investigations. From Table 6 it can be concluded that using a linear equation for describing the relationship between VI and G/R_n is adequate and agrees with past studies. The analytical derivation of the VI–G/R_n relationships showed that linear relationships would exist if the coefficients β and τ were equal in sign and magnitude. The results from Table 4 and 5 show that $\beta \approx 0.5$ and that $\tau \approx 1.3$ for NDVI while the exponential expression between NIR / Red and LAI yielded $\tau \approx 0.4$. However, from the comparison of NIR / Red and LAI values in Figure 6b and from the regression results in Table 5, a linear relationship between NIR / Red and LAI appears more suitable. Hence the linear equations between G/R_n and VI listed in Table 6 do not conform to the analytical results given by Eqs. (5) and (7).

A linear relationship between VI and G/R_n also does not agree with the exponential equation obtained by substituting a linear NIR / Red–LAI expression into Eq. (2). Furthermore, a linear relationship between VI and G/R_n does not follow from substitution of a linear NIR / Red–LAI expression into Eq. (8) defining NDVI, which is then substituted into Eq. (2).

The data for midday G/R_n were also evaluated using the nonlinear expression given by Eq. (9). Table 7 lists the regression results for fitting this relationship with NIR / Red and NDVI. In Figure 7 are the linear and power relationships fit to the data. For NIR / Red, the nonlinear relationship in Figure 7a appears to fit the data better than a linear expression. But results listed in Tables 6 and 7 are not as convincing. For the NDVI–G/R_n relationship, the results in Tables 6 and 7, and the comparison illustrated in Figure 7b suggest a nonlinear equation is not supported by the data.

Comparison of VI Formulas for Estimating G

A sensitivity analysis of the VI formulas for estimating G was performed by using a range of values for NIR / Red and NDVI and R_n to compute G. Table 8 lists the VI and R_n values used in the sensitivity analysis, along with the formulas. The only formula not used in the intercomparison was the nonlinear equation [i.e., Eq. (9)] using NDVI as the independent variable since the data did not support such a relationship (see Fig. 7b).

A comparison of model output with the different equations is illustrated in Figure 8. Differences in G

Table 5. Statistical Results Fitting Eqs. (4) and (6) and a Linear Equation between LAI and NIR / Red with the Data from Table 3

Vegetation Index	*Equation*	*Coefficients*	R^2	*Root Mean Square Error*[a]
NIR / Red	NIR / Red = A LAI + B	$A = 3.83$ $B = 2.24$	0.85	3.77
NIR / Red	NIR / Red = A exp(τ LAI)	$A = 2.45$ $\tau = 0.43$	0.79	10.10
NDVI	NDVI = A [1 − B exp(− τ LAI)]	$A = 0.90$ $B = 0.86$ $\tau = 1.26$	0.97	0.05

[a] $\mathrm{RMSE} = \left[\sum_{i=1}^{n} (E_i - O_i)^2 / n \right]^{1/2}$, where E_i is the model estimate and O_i is the observation and n is the number of data points.

Table 6. Comparison of Regression Equations from This Study and Other Investigations Using G/R_n as a Linear Function of VI

Vegetation Index	*Source*	R^2	*Number of Data Points*	*Slope (SE)*[a]	*Intercept*	*SE*[a] *of* G/R_n *Estimate*
NIR / Red	Present study	0.70	42	−0.0094 (±0.001)	0.30	0.06
	Kustas and Daughtry (1990)	0.74	11	−0.017 (±0.004)	0.32	0.04
	Clothier et al. (1986)	0.87	74	−0.013 (±0.009)	0.35	0.01
NDVI	Present study	0.80	42	−0.33 (±0.026)	0.40	0.05
	Kustas and Daughtry (1990)	0.86	11	−0.21 (±0.03)	0.32	0.02

[a] Standard error.

estimated by the equations are generally within ±50 W m^{-2}. This translates to a variation of 25–100% of the average value, depending on the magnitude of G and the equation being used. An interesting feature in this plot is that the linear equations using NIR / Red tend to calculate larger values of G (in magnitude) for the intermediate VI cases compared to the equations using NDVI and Eq. (9) with NIR / Red. Also note for the high VI case that one of the linear equations with NIR / Red calculates a positive G, indicating an upward soil heat flux to the surface. Another important feature from this figure is that the two linear equations using NDVI and Eq. (9) with NIR / Red give similar values of G over the whole range in VI values. In fact, the average difference between these three equations is less than ±25 W m^{-2}. Therefore, G values estimated by these formula are likely to give more consistent results over a wider range in VI than the linear equations using NIR / Red.

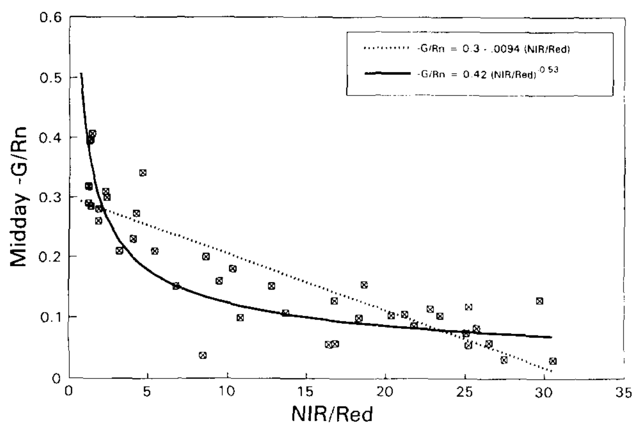
CONCLUSIONS

Analytical expressions were derived from the relationship between midday soil heat flux / net radiation ratio and NIR / Red ratio and NDVI. The data from bare soil and soybean crops from BARC 89, under a range of vegetation cover in a humid region, were combined with data collected over alfalfa, cotton, and bare soil in an arid climate during MAC 88. Comparison of the field measurements of VI and midday G/R_n showed that a linear equation was an adequate description of the relationship while equations derived from analytical considerations suggested nonlinear expressions. Nevertheless, the VI–LAI and G/R_n–LAI relationships used to derive the equations between VI and G/R_n were either empirical or, if physically based, were oversimplified to obtain a solution. Thus, a lack of agreement between the analytical solutions and field data was more likely. On the other hand, this analytical exercise did point out that nonlinear relationships between VI and G/R_n are more plausible. Indeed, the NIR / Red data supported this conclusion, at least qualitatively (see Fig. 7a).

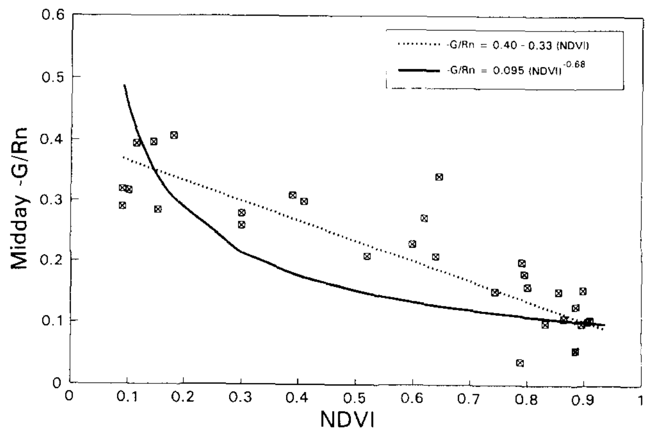
Table 7. The Statistical Results Describing G/R_n as a Power Function [Eq. (9)] of VI

Vegetation Index	*a*	*b*	R^2	*RMSE*
NDVI	0.095	−0.68	0.51	0.08
NIR / Red	0.42	−0.53	0.70	0.05

Figure 7. G/R_n versus VI with a linear and a power function expression [Eq. (9)] for a) NIR / Red and b) NDVI.



(a)



(b)

Table 8. Values of NIR / Red, NDVI, and R_n Used in the Formulas Listed for Calculating G

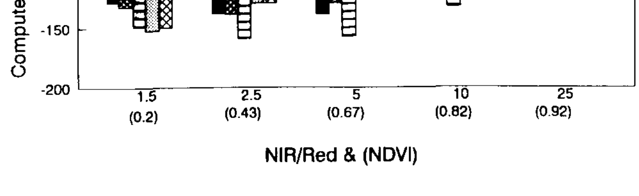
NIR / Red	NDVI	R_n ($W\ m^{-2}$)
0.5	0.2	450
2.5	0.43	500
5	0.67	550
10	0.82	600
25	0.92	650
Formulas for Computing G / R_n		
0.3 − 0.0094 NIR / Red		
0.32 − 0.017 NIR / Red		
0.35 − 0.013 NIR / Red		
0.42 (NIR / Red)$^{-0.53}$		
0.40 − 0.33 NDVI		
0.32 − 0.21 NDVI		

Of greater importance is the sensitivity of the coefficients of the linear and nonlinear expressions to changes in vegetation type, soils, and environmental conditions. In other words, can a simple expression for estimating midday G / R_n using a VI yield reliable results over large areas without having to significantly alter the coefficients due to changes in surface or environmental conditions?

The sensitivity analysis of the VI formulas for estimating G listed in Table 8 and the comparison illustrated in Figure 8 document that significant variability in computed values can exist. But the linear equations using NDVI and the nonlinear equation [Eq. (9)] using NIR / Red produced relatively small differences over the whole range in VI values.

The simplicity of this approach combined with the availability of global maps of VI (Ohring et al., 1989) makes it easy to incorporate into operational models computing large area energy fluxes. Therefore, field measurements over different surfaces and under a wider range of environmental conditions for testing the universality of G / R_n–VI relationships are warranted. In addition, the relationships between vegetation indices which are not as sensitive to background soil reflectances and G / R_n should be investigated.

Figure 8. Comparison of soil heat flux computed by the equations and values of VI and R_n listed in Table 8.



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REFERENCES

André, J. C., Goutorbe, J. P., and Perrier, A. (1986), HAPEX-MOBILHY: A hydrological atmosphere experiment for the study of water budget and evaporation flux at the climatic scale, *Bull. Am. Meteor. Soc.* 67:138–144.

Asrar, G., Fuchs, M., Kanemasu, E. T., and Hatfield, J. L. (1984), Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectances in wheat, *Agron. J.* 76:300–306.

Asrar, G., Myneni, B. R., and Kanemasu, E. T. (1989), Estimation of plant canopy-attributes from spectral reflectance measurements, in *Theory and Applications of Optical Remote Sensing* (G. Asrar, Ed.), Wiley, New York, pp. 252–296.

Baret, F., and Guyot, G. (1991), Potentials and limits of vegetation indices for LAI and APAR assessment, *Remote Sens. Environ.* 35:161–173.

Baret, F., Guyot, G., and Major, D. (1989), TSAVI: a vegetation index which minimizes soil brightness effects on LAI and APAR estimation, in *12th Canadian Symposium on Remote Sensing and IGARSS '90*, Vancouver, Canada, 10–14 July 1989, pp. 1355–1358.

Biehl, L. L., and Robinson, B. F. (1983), Data acquisition and preprocessing techniques for remote sensing field research, *Proc. Soc. Photo-Opt. Instrum. Eng.* 356:143–149.

Brunel, J. P. (1989), Estimation of sensible heat flux from measurements of surface radiative temperature and air temperature at two meters: application to determine actual evaporation rate, *Agric. For. Meteorol.* 46:179–191.

Brutsaert, W. H. (1982), *Evaporation into the Atmosphere*, Reidel, Boston, 299 pp.

Camuffo, D., and Bernardi, A. (1982), An observational study of heat fluxes and their relationships with net radiation, *Boundary-Layer Meteorol.* 23:359–368.

Choudhury, B. J., Idso, S. B., and Reginato, J. R. (1987), Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infrared-temperature based energy balance equation, *Agric. For. Meteorol.* 39:283–297.

Clevers, G. A. P. W. (1989), The application of a weighted infrared-red vegetation indices for estimating leaf area index by correcting for soil moisture, *Remote Sens. Environ.* 29:25–37.

Clothier, B. E., Clawson, K. L., Pinter, P. J., Moran M. S., Reginato, R. J., and Jackson, R. D. (1986), Estimation of soil heat flux from net radiation during the growth of alfalfa, *Agric. For. Meteorol.* 37:319–329.

Daughtry, C. S. T., Gallo, K. P., Goward, S. N., Prince, S. D., and Kustas, W. P. (1992), Spectral estimates of absorbed radiation and phytomass reproduction in corn and soybean canopies, *Remote Sens. Environ.* 39:141–152.

Day, P. R. (1965), Particle fractionation and particle-size analysis, in *Method of Soil Analysis, Part I* (C. A. Black et al., Eds.), *Agronomy* 9:545–567.

De Vries, D. A. (1963), Thermal properties of soil, in *Physics of the Plant Environment* (W. R. van Wijk, Ed.), North-Holland, Amsterdam, pp. 210–235.

Field, R. T., Fritschen, L. J., Kanemasu, E. T., et al. (1992), Calibration, comparison and correction of net radiation instruments used during FIFE, *J. Geophys. Res.* 97(D17): 18,681–18,696.

Fritschen, L. J., and Gay, L. W. (1979), Environmental Instrumentation in *Springer Advanced Texts in Life Sciences* (D. E. Reichler, Ed.), Springer-Verlag, New York.

Fuchs, M., and Hadas, A. (1972), The heat flux density in a nonhomogeneous bare loessial soil, *Boundary-Layer Meteorol.* 3:191–200.

Goward, S. A., Tucker, C. J., and Dye, D. (1985), North American vegetation pattern observed with NOAA-7 Advanced Very High Resolution Radiometer, *Vegetation* 6:3–14.

Gurney, R. J., and Camillo, P. J. (1984), Modelling daily evapotranspiration using remotely sensed data, *J. Hydrol.* 69:305–324.

Hatfield, J. L., Kanemasu, E. T., Asrar, G., et al. (1985), Leaf area estimates from spectral measurements over various planting dates of wheat, *Int. J. Remote Sens.* 6:167–175.

Hinzman, L. D., Bauer, M. E., and Daughtry, C. S. T. (1986), Effects of nitrogen fertilization on growth and reflectance characteristics of winter wheat, *Remote Sens. Environ.* 19: 47–61.

Holben, B. N., Tucker, C. J. and Fan, C. J. (1980), Spectral assessment of soybean leaf area and leaf biomass, *Photogramm. Eng. Remote Sens.* 46:651–656.

Huete, A. R. (1987), Soil and sun angle interactions on partial canopy spectra, *Int. J. Remote Sens.* 8:1307–1317.

Huete, A. R. (1988), A Soil-Adjusted Vegetation Index (SAVI), *Remote Sens. Environ.* 25:295–309.

Huete, A. R., Jackson, R. D., and Post, D. F. (1985), Spectral response of a plant canopy with different soil backgrounds, *Remote Sens. Environ.* 17:37–53.

Idso, S. B., Aase, J. K., and Jackson, R. D. (1975), Net radiation-soil heat flux relations as influences by soil water content variations, *Boundary-Layer Meteorol.* 9:113–122.

Jackson, R. D. (1985), Evaluating evapotranspiration at local and regional scales, *Proc. IEEE* 73:1086–1095.

Jackson, R. D., Reginato, R. J., and Idso, S. B. (1977), Wheat canopy temperature: a practical tool for evaluating water requirements, *Water Resour. Res.* 13:651–656.

Jackson, R. D., Moran, M. S., Gay, L. W., and Raymond, L. H. (1987), Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data, *Irrig. Sci.* 8:81–90.

Kustas, W. P., and Daughtry, C. S. T. (1990), Estimation of the soil heat flux / net radiation ratio from spectral data, *Agric. For. Meteorol.* 49:205–233.

Kustas, W. P., Moran, M. S., Jackson, R. D., et al. (1990), Instantaneous and daily values of the surface energy balance over agricultural fields using remote sensing and a reference field in an arid environment, *Remote Sens. Environ.* 32:125–141.

Kustas, W. P., Goodrich, D. C., Moran, M. S., et al. (1991), An interdisciplinary field study of the energy and water fluxes in the atmosphere-biosphere system over semiarid rangelands: description and some preliminary results, *Bull. Am. Meteorol. Soc.* 72:1683–1705.

Monteith, J. L. (1973), *Principles of Environmental Physics*, Elsevier, New York, 241 pp.

Nie, D., Kanemasu, E. T., Fritschem, L. J., et al. (1992), An intersensor comparison of surface energy flux for FIFE, *J. Geophysical Res.* 97(D17):18,715–18,724.

Ohring, G., Gallo, K., Gruber, A., Planter, W., Stowe, L., and Tarpley, J. D. (1989), Climate and global change, characteristics of NOAA satellite data. *EOS* 70(41):889–901.

Oliver, H. R., and Wright, I. R. (1990), Correction of errors associated with measurement of net all-wave radiation with double-dome radiometers, *Boundary-Layer Meteorol.* 53: 401–407.

Ormsby, J. P., Choudhury, B. J., and Owe, M. (1987), Vegetation spatial variability and its effect on vegetation indices, *Int. J. Remote Sens.* 8:1301–1306.

Perry, C. R., and Lautenschlager, L. F. (1984), Functional equivalence of spectral vegetation indices, *Remote Sens. Environ.* 14:169–182.

Philip, J. R. (1961), The theory of heat flux meters, *J. Geophys. Res.* 66:571–579.

Price, J. C. (1982), Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data, *IEEE Trans. Geosci. Remote Sens.* GE-20:286–292.

Ranson, K. J., Daughtry, C. S. T., Biehl, L. L., and Bauer, M.E. (1985), Sun-view angle effects on reflectance factors of corn canopies, *Remote Sens. Environ.* 18:147–161.

Ritchie, J. T. (1972), Model for predicting evaporation from a row with incomplete cover, *Water Resources Res.* 8(5): 1204–1213.

Ross, J. (1981), The radiation regime and architecture of plants in *Tasks for Vegetation Sciences 3* (H. Lieth, Series Ed.). Dr. W. Junk, The Hague, Netherlands.

Sellers, P. J., Hall, F. G., Asrar, G., Strebel, D. E., and Murphy, R. E. (1988), The first ISLSCP field experiment (FIFE), *Bull. Am. Meteorol. Soc.* 69:22–27.

Seguin, B., and Itier, B. (1983), Using midday surface temperature to estimate daily evaporation from satellite thermal IR data, *Int. J. Remote Sens.* 4:371–383.

Shuttleworth, J. W., Gurney, R. J., Hsu, A. Y., and Ormsby, J. P. (1989), FIFE: the variation in energy partition at surface flux sites, in *Proceedings of the IAHS Third Int. Assembly*, Baltimore, IAHS Publ. No. 186, pp. 67–74.

Taconet, O., Carlson, T., Bernard, R., and Vidal-Madjar, D. (1986), Evaluation of a surface / vegetation parameterization using satellite measurements of surface temperature, *J. Climate Appl. Meteorol.* 25:1752–1767.

Tucker, C. J., Townshend, J. R. G., and Goff, T. E. (1985), African land-cover classification using satellite data, *Science* 227:369–375.

Van Oevelen, P. J. (1991), Determination of the available energy for evapotranspiration with remote sensing, MSc. thesis, Wageningen Agricultural University.

Van de Griend, A. A., and van Boxel, J. H. (1989), Water and surface energy balance model with a multilayer canopy representation for remote sensing purposes, *Water Resour. Res.* 25:949–971.

Van de Griend, A. A., Owe, M., Vugts, H. F., and Prince, S. D. (1989), Water and surface energy balance modeling in Botswana, *Bull. Am. Meteorol. Soc.* 70:1404–1411.

Verhoef, W. (1984), Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model, *Remote Sens. Environ.* 16:125–141.

Wiegand, C. L., Gerberman, A. H., Gallo, K. P., Blad, B. L., and Dusek, D. (1990), Multisite analyses of spectral-biophysical data for corn, *Remote Sens. Environ.* 33:1–16.